DU BOIS

Variable-Speed Direct-Current Motors

Electrical Engineering

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VARIABLE-SPEED DIRECT-CURRENT MOTORS

BY

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B. S. University of Illinois, 1899

THESIS

Submitted in Partial Fullfillment of the Requirements for the

Degree of

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Alexander Dawes Du Bois

ENTITLED Variable Speed Direct Current Motors

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Electrical Engineer

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VARIABLE SPEED MOTORS.

The Principles, Types and Characteristics of Variable-speed Direct-current Motors for Industrial Service.

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For the individual motor-drive of many of the metal-working machine-tools, and other machines requiring changes of speed, a direct-current variable-speed system, in some form, is essential to the maximum economy of production. There are a number of variable-speed motors on the market, based upon different principles of speed-control and representing various forms of design. In order to choose the equipment best adapted to the requirements of a given shop, or a given machine, it is necessary to have a clear understanding of the principles involved in the variation of motor speed, and the torque-speed characteristics inherent in the several methods of control.

The speed of any motor is necessarily such that the counter e.m.f. generated in the armature will fall short of balancing the applied e.m.f. of the line by just sufficient voltage to force the required current through the resistance of the armature. The required current referred to, is that current necessary to produce the torque imposed by the load on the motor. If the motor should for an instant fall below the speed above specified, the counter e.m.f. would decrease, allowing more current to pass through the armature; but the greater current would produce greater torque which would accelerate the motor to the

required speed. Thus the motor automatically adjusts its speed to a certain value which it maintains so long as the conditions are unaltered.

If we increase the voltage impressed at the armature terminals, other conditions remaining constant, the counter e.m.f. must automatically increase, to prevent greater current in the armature, and therefore the armature must rotate at higher speed. This is evident by supposing the speed to remain unchanged and considering the consequences. The greater voltage would cause greater armature current thus producing torque in excess of the load, which would necessarily result in acceleration. By changing the impressed armature voltage we can therefore change the speed of a motor.

If we decrease the flux-density of the magnetic field of the motor, other conditions remaining constant, the armature is compelled to run at higher speed in order to generate the required counter e.m.f. If it did not do so, the reduced counter e.m.f. brought about by weakened field would admit greater current into the armature thus bringing about the result of acceleration. This, then, is a second method of varying the speed.

The total counter e.m.f. is the sum of the e.m.f.'s of all the separate armature conductors in series. If fewer conductors are in series, each must generate a greater e.m.f. in order to produce the same total. If the number of armature conductors in series in a given motor be reduced, other conditions remaining constant, the speed of the motor must increase in order to maintain the required counter e.m.f. A third method of speed

variation is thus made available.

These three devices are the only possible means by which the speed of a d.c. motor can be varied.

Since the speed varies directly as counter e.m.f. and inversely as the field flux and number of armature conductors in series, we may write

$$v = \frac{e}{\Phi Y}$$

Where v = speed (in some undetermined unit)

e = counter e.m.f. = a function of impressed voltage.

Y = number of active armature conductors in series from brush to brush.

The counter e.m.f., e, $= E - IR_a$ and is so nearly equal to the impressed voltage, E, that it is approximately correct, for the present purpose, to write

$$v = \frac{E}{\Phi Y}$$

It is commercially feasible to vary any one of the factors E, ϕ, or Y as a means of producing variable speed; in fact the variation of each of these factors has been made the basis of several different types of motors which are or have been used in commercial practice. In the accompanying chart (Table I) the commercially applied methods of speed control are classified in accordance with the basic principles upon which they are founded, and on the right of the chart they are also referred to the requisite systems of power distribution. In discussing these methods of speed control in detail, the arrangement of the chart will be followed, taking up each method in its relation to the fundamental principle involved. The four systems of distribution, viz., single voltage, equal voltage three-wire, unequal-voltage

three-wire, and four-wire multi-voltage, will be described in connection with the methods of control to which they apply.

TABLE I.

A CLASSIFICATION OF DIRECT CURRENT VARIABLE SPEED MOTORS

BASIC PRINCIPLE OF SPEED CONTROL	GENERAL METHOD	SPECIFIC METHOD	DISTRIBUTING SYSTEM
Changing Voltage Impressed on Armature	Connecting to Circuits of Different Voltages	Equal Voltage Three-Wire System	Three-Wire System Using 3 Wires
		Unequal Voltage Three-Wire System	Multiple Voltage Using 3 Wires
		Multi-Voltage Four-Wire System	Multiple Voltage Using 4 Wires
	Resistance in Armature Circuit	Armature Rheostatic Control	Single Voltage Using Two Wires
	Varying Voltage by Auxiliary Motor-Generators	Motor-Generator System	
		Boost and Retard System	
		Teaser System	
Changing Field Magnetism	Shunt Field Control (By Resist. in Field Circuit)	Standard Motors	
		Compensated Motors	
		Inter-pole Motors	
	Varying Reluctance of Magnetic Circuit	Moving Poles Radially	
		Moving Armature Longitudinally	
	Shunting Part of Field Current	Used with Series Motors	
Changing Number of Conductors in Series Between Brushes	Series-Parallel Control	Double Commutator Motors	
	Changing Number of Poles	Obsolete	

VARIABLE SPEED BY CHANGING E.M.F. IMPRESSED ON ARMATURE.

It has been shown that, with other conditions constant, the speed of a given motor must vary directly as its counter e.m.f. The counter e.m.f. is equal to the voltage impressed upon the armature minus IR drop in armature and brushes. Since the armature and brush drops are relatively very small, any change in the voltage impressed upon the armature terminals will produce a nearly proportional change in speed.

Speed variation by this method does not change the full-load torque which the motor is capable of exerting, since rated torque depends only upon field flux and rated armature current. Hence the methods depending upon this principle of control are inherently constant torque methods and are properly adapted to loads in which the torque remains constant regardless of the speed. Pumps, hoists and printing-presses are examples of such loads.

The normal speed of the motor is the maximum speed of its range, the maximum employed voltage being that for which the motor is designed, and the natural speed changes being downward from normal speed to zero. Since torque remains constant, the available power output varies directly as the speed. A motor to give constant horse-power, by these methods, through a range of 2 to 1, must therefore be twice as large as a motor to deliver the same horse-power at the maximum speed only, and for a range of 4 to 1 it will be four times as large as necessary at the highest speed.

There are several methods of changing the e.m.f. at the motor terminals. The three-wire system, the various systems

of multiple voltage, ordinary armature rheostatic control and several motor-generator schemes are used in their respective fields of application.

INSERTING RESISTANCE IN ARMATURE CIRCUIT.

(Armature Rheostatic Control)

The simplest method of varying the voltage impressed upon the armature is by means of a regulating resistance in the armature circuit. Assuming constant line voltage E, and remembering that

$$E = \text{c.e.m.f.} + IR_a + IR_b + IR_x$$

where I = armature current

R_a = Resistance of armature

R_b = Resistance of brushes and contacts

R_x = Resistance of rheostat.

it is seen that if the ohmic drop IR_x be increased, the c.e.m.f. must decrease in order to maintain the equality. The reduction of counter e.m.f. takes place through a proportional reduction of speed.

Inherent Regulation:- The voltage at the armature terminals is equal to line-voltage minus the IR drop in the rheostat. Any change of load with its accompanying change of armature current, will cause a change of IR drop in the rheostat and therefore a change in the terminal voltage at the motor. The speed of the armature must change in order to meet this new requirement of voltage. The result is, that very great speed changes are brought about by fluctuations in the load, especially when the controller is set for slow speeds. Fig. 1 shows graphically, for an 825 r.p.m. motor, the relation of speed to torque

for four different settings of the controller, and indicates at a glance the poor regulation when much resistance is in circuit. Referring for example to the controller setting represented by curve, b, and assuming the load to be reduced while running, from rated torque to one-fourth rated-torque, it is seen that the speed will rise from approximately 410 to 750 r.p.m. Such a change might be brought about by a reduction of the cut taken by a machine-tool and in such a case would endanger both work and tool.

Efficiency:- If the motor operates at constant torque the output will be directly proportional to speed. Also, the armature current will be constant to produce constant torque, and if the line voltage remains unchanged the input to the combination of motor* and rheostat will be constant and equal to $I_t E$.

where I_t = total motor current, and E = line voltage.

$$\text{Efficiency of combination} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{A constant}}$$

But the output varies as the speed, (neglecting variation of stray-power with speed); therefore efficiency varies approximately with speed as shown by the straight lines of Fig. 2. It is sufficient for ordinary purposes, to determine the efficiency at one speed and draw a straight line through the origin. The efficiency referred to is of course that of the motor plus controller and not of the motor alone, and the example is based upon constant torque at all speeds. Should the character of the load be such that the torque will decrease with decreasing speed, the power lost in the rheostat will be of much less importance.

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*The copper loss in the field windings is constant.

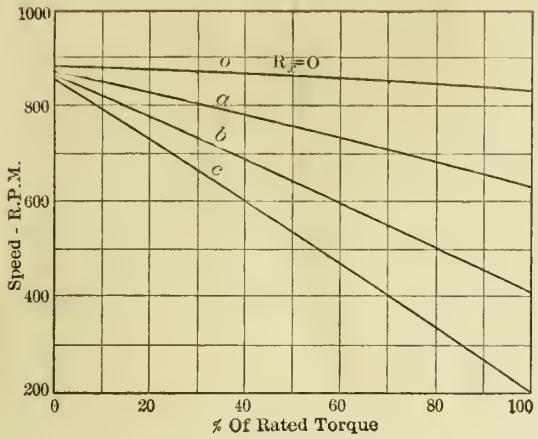

Fig. 1. Speed-Torque Curves
Armature Rheostatic Control

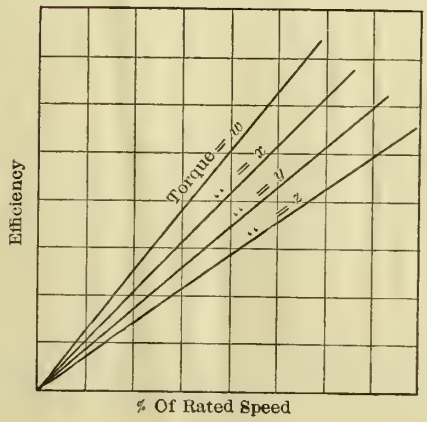

Fig. 2. Variation of Efficiency with Speed. Arm. Rheo. Control.

This method of control has its largest field of usefulness in the operation of series motors for cranes, hoists, and railways, but it may also be considered good practice in connection with either shunt, series, or compound motors, for the control of pumps, fans, blowers, or any other machines in which the power-demand decreases rapidly with decrease of speed.

The limitations of the method are such as to render it wholly unsuited for general variable speed service in shops. These limitations may be briefly summarized as follows:

1. If the motor load varies, that portion of the voltage which is lost in the rheostat, is altered, and this changes the speed of the motor, producing exceedingly poor regulation. The motor will slow down under heavy loads.
2. The efficiency is very low at slow speeds because that percentage of the total voltage which is lost in the rheostat, represents an equal percent complete loss of power.
3. The rheostat necessary to dissipate so much wasted power is of bulky size, and could not be mounted near motor where space is limited.

CONNECTING TO CIRCUITS OF DIFFERENT VOLTAGES.

All methods of distribution which employ more than two wires, affording more than one voltage and thereby enabling standard motors to be operated at different speeds by connecting their armature terminals to circuits of different potentials, may be broadly termed "multiple-voltage" systems. There are

three systems in use which come under this heading.

1st, A three-wire system in which the neutral or "third-wire" is maintained at a potential midway between the potentials of the other two wires. This will be referred to as "the equal voltage three-wire system".

2nd, A three-wire system with unequal voltages, and

3rd, A four-wire system with unequal voltages.

A five-wire system although quite possible, is manifestly undesirable, and has not and probably will not come into commercial use.

The "equal voltage" three-wire system will give two variations of speed; the "unequal" three-wire system, three variations; and the four-wire system, six variations, by voltage control alone. By properly combining multiple-voltage and field control, the minimum size of standard motor without special variable speed design, can be used to produce constant power throughout a given range of speed. In order to use the smallest possible motor, for constant output at all speeds, the field weakening on highest voltage should be carried to a point where the safe rating of the motor, due to its sparking limitations, is just equal to its rating on full field and lowest voltage, due to heating limitations.

Three-Wire System with Equal Voltages. The three-wire balanced-voltage system for variable-speed work is in several respects, a compromise between the single voltage systems and the more elaborate systems of multi-voltage. It has long been in use as a standard system of distribution for lighting, and in this role is well known as the Edison three-wire system.

In its adaptation to motor drive, the distributing

system consists of three-wires which are led to every variable-speed motor. The generator may be either a standard machine, with a separate balancer set as shown in Fig. 3, or it may be a three-wire generator, one type of which is indicated in Fig. 4. There are several types of three-wire generators depending upon the action of an auto-transformer to maintain a balance of e.m.f. in the two halves of the generator armature. The generator shown in Fig. 4 is a standard machine with the addition of slip rings which are connected to the armature windings, and which lead out, through brushes, to the terminals of a choke coil, or auto-transformer. The middle point of the choke coil winding is connected with the neutral wire of the three-wire system. By this device it is possible to dispense with the usual balancer set. Two-commutator generators have been used to supply three-wire systems without balancer sets, but they are practically obsolete for this purpose.

In the three-wire systems as most commonly employed for power purposes, a balancer-set is installed to maintain the balance of voltage. This balancer need not be in the power plant; it is usually located near the center of distribution for the variable speed motors. The voltages at the motors, are usually, 220 volts between outside wires and 110 volts between each outside wire and the neutral. The motor fields are energized by the 220 v. circuit; the necessary variation of field excitation being secured by inserting resistance in the usual manner. The armature is operated on 110 v. for the low speeds and on 220 v. for the high speeds. The normal range of speed is 4 to 1. In order to trace the several steps in the speed variation on this system, assume that a given motor is required to

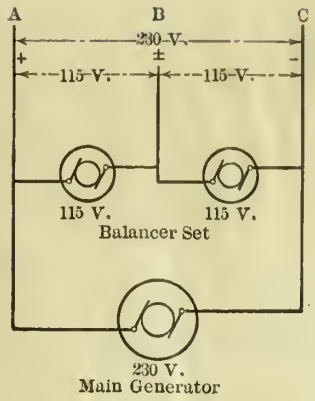

Fig. 3. Three-Wire Equal-Voltage System.
With Balancer

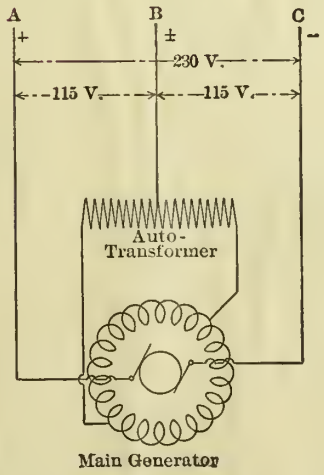

Fig. 4. Three-Wire Equal-Voltage System
Three-Wire Generator

operate at a speed ranging from 300 to 1200 r.p.m. Let the motor selected for this service be a standard 220 volt motor with a normal speed of 600.

It is first started by connecting its field to the 220 volt circuit without resistance, and its armature to one of the 110 volt circuits with starting resistance in series. The first few steps of the controller serve merely to cut the starting resistance out of circuit and to bring the motor up to the minimum speed of its working range. Now the field of the motor is fully excited but the armature has impressed upon it only half of its normal voltage; hence the speed is half of normal, which in the present example is 300 r.p.m.

The speed is next increased, by inserting resistance in the field circuit, until a speed of 600 r.p.m. has been attained. This is the normal speed of the motor - the speed at which it is built to operate on 220 volts with normal field excitation - and the speed therefore at which it will run if the armature be thrown over to the 220 volt circuit and the field simultaneously increased to full strength. This is the step next performed by the controller. It cuts out all field resistance, and at the same time, connects the armature to the outside wires. The field will not come to full strength instantly, because of self-induction, and a resistance is therefore thrown into circuit with the armature during this period of transition; it is in circuit for a very short interval only. The motor is now running on full field with 220 volts impressed on the armature. The last steps of the controller repeat the weakening of the field until the speed is 1200 r.p.m. By this means a speed range of 4 to 1 is obtained with the standard type of shunt-wound motor, without

resorting to a motor of excessive size. The changes from one voltage to the other, and the variation of the field resistance are all accomplished by a single controller, usually of the drum type, of moderate size and of simple construction as compared with multi-voltage controllers but more complicated and subject to disorder than controllers for purely shunt field control.

If the driven machines are such as to require constant power with varying speed, the motors must be so rated that they will deliver their rated output at all speeds throughout the range. On this basis they are good for about twice their rated horse-power on the high voltage at full field strength. As an example, assume that a certain machine requires 7 1/2 h.p. throughout a speed range of 4 to 1, and let the speeds required of the motor be from 300 to 1200 r.p.m. On the three-wire system this motor will be a 15 h.p., 220 volt motor, at 600 r.p.m. It will be standard in all respects but must have suitable sparking constants. On 110 volts with full field it will develop 7 1/2 h.p., and will run at 300 r.p.m. On the same circuit with weak field so that the speed is say 520 r.p.m., it will still develop about 7 1/2 h.p. if the design has good commutating characteristics. The next step throws the armature upon 220 volts with full field, and under these conditions it is a 15 h.p. motor at 600 r.p.m. Therefore only half load is required of the motor on 220 volts, and when the field is weakened to half strength to give maximum speed, the motor is required to commutate only half its normal current.

Speed regulation on the three-wire system is much better than with the four-wire multi-voltage systems, but is not so good as with a single voltage system using all field control. This

is due to the fact that the IR drop, through the armature and other resistances, is a greater percent of total impressed voltage when running on the lower voltage. The effect of lowering the voltage where constant power is required, is twofold; not only is the total voltage cut in half, but the current required for the given output is doubled; hence the IR drop is doubled, and the percentage drop (over that which will obtain for the same motor on the higher voltage) is multiplied by four. It should be pointed out, however, that the normal current on the high voltage is only half that for which the standard motor was designed.

The efficiency of the motors, as well as of the entire system, is fairly satisfactory. On the low voltage the motors are under full-load conditions, with corresponding efficiency, which decreases but slightly as the speed is increased by field control. On the high voltage, the motors are under the condition of half load, at which point the efficiency is only fairly good.

The efficiency of transmission on the three-wire system is high, because practically all the current is transmitted at maximum voltage. In other words, an important feature of the system, and one which affects efficiency, as well as regulation, is the very small unbalance to which it is subject when properly installed. Since the voltages on both sides of the neutral are the same, the motors can be installed so that half of them will have their low voltage connections on one side of the system and half of them on the other side. In this way, the percentage of unbalance can be kept much smaller than is possible with unequal voltage systems. The constant-speed motors are connected across

the outside wires, and do not affect the balance of the system. Light is available from the same mains, with the advantages which attach to a three-wire lighting system. 110-volt lamps are equally distributed between the two sides of the system so that the unbalancing from this cause is very slight.

In what has preceded, the motors are assumed to be working under the condition of constant output at all speeds, this being the characteristic of the majority of motor-driven machine-tools. However, many loads require constant torque. The system is especially applicable to such cases, and for the intermediate speed-steps, armature rheostatic control may replace field control. The three-wire system of distribution therefore affords the means of properly serving various kinds of loads; the constant power loads may be driven by single voltage inter-pole motors with simple field control, using only the outside wires, while the constant-torque loads are served by the two-voltage control.

Three-Wire Unequal Voltage System: This differs from the equal-voltage three-wire system in the relative voltages employed between neutral and outside wires. The system as originated by the Bullock Electric Manufacturing Company is indicated in Fig. 5. The balancer-set, or compensator, consists of two dynamo-machines mechanically coupled together and with their armatures electrically in series. Thus far it is like the equal voltage balancer; but in the present case one of the armatures is wound for 90 volts, the other for 160. This makes three voltages available on the distributing system, viz., 90, 160 and 250 volts. These voltages and the resulting fundamental speed-steps of the motors are in approximately geometrical pro-

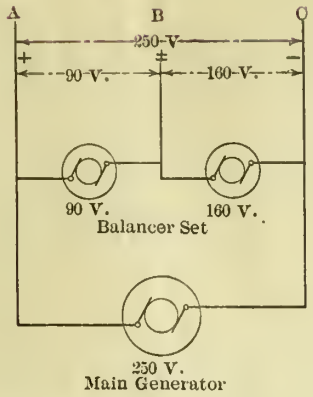

Fig. 5. Three-Wire Un-equal-Voltage System

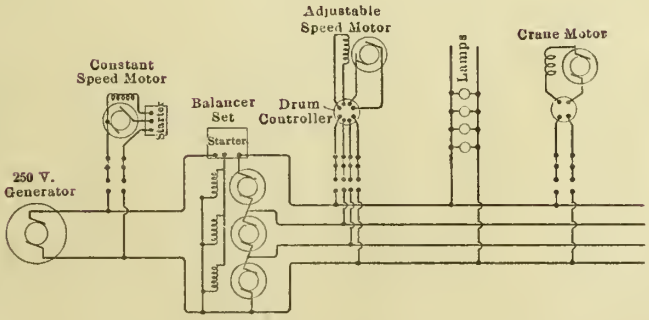

Fig. 6. General Scheme of Multiple Voltage Distribution

gression, each voltage being about 67% higher than the voltage next below. The steps between voltages, and above the highest voltage, are ordinarily obtained by shunt field control. The Allis-Chalmers Bullock system gives a total of 12 speeds forward and nine in the reverse direction, the three highest speeds being not usually required for reversed running. The total speed-range by voltage-control alone, is evidently the ratio of the limiting voltages or $\frac{250}{90}$ = approximately 2.6 to 1. The field control is so proportioned as to give speed steps of about 20 percent each.

External resistance is introduced into the armature circuit when starting the motor, and also when passing from one voltage to the next, but the latter is merely for the purpose of easing the transition as previously explained, and it is automatically cut out by a solenoid switch as soon as its purpose has been accomplished.

This system is subject to greater unbalance than the equal-voltage three-wire system for the reason that the low voltage connections of the motor cannot be distributed between the two sides of the system. If all the motors were to run on the lowest voltage at the same time, the entire variable speed motor load would be on one side of the system. This extreme condition would never occur in practice, but the system's liability to unbalance has a direct bearing upon the size of wires and capacity of balancer-set which must be installed for a given loss of voltage in transmission.

As in the preceding system, constant speed motors and crane motors are operated on the outside wires or highest voltage, and in order that standard lamps, all of the same volt-

age, may be used, they too are usually connected to the outside wires.

Four-Wire Multiple Voltage Systems. These systems are extensions of the three-wire unequal voltage idea. Four wires are used for distribution, making six voltages available. The power is supplied by a standard generator, and the balance of voltage on the several circuits is maintained by a balancer-set, consisting of three machines of suitable voltages, coupled together in the same manner as three-wire balancers.

The six voltages give six fundamental motor speeds, which are subject to further refinement by varying the motor's field strength through a range sufficient to cover the gaps between voltages. The usual speed-range is about six or seven to one, but it is possible by means of field control above the highest voltage step, to increase this range to 10 to 1 or even further, depending upon the amount of field weakening which the motor will stand without sparking. The general scheme of these systems is shown in Fig. 6. The four wires are led to all variable-speed motors, but only the two outside wires need be led to constant speed motors, lamps, crane motors and elevator motors. Motors requiring only a comparatively small range of speed and working at constant power throughout the range can be connected across the outside wires and controlled by field weakening exclusively, while machines requiring a wide range and especially those having the constant-torque characteristic, are served by the multiple voltage mains.

The change of unbalancing is less with the four wire system than with the three-wire arrangement having unequal voltages, since the probability that a given number of motors will

operate at one time on the same voltage is manifestly less where six voltages are used than it would be with only three. In the multi-voltage system, there are really two neutral wires, and they must be larger than the neutral of the equal voltage three-wire system, in-as-much as the unbalancing is likely to be greater; in fact, all of the wires must be larger, if the same percentage of line loss is to be maintained.

Since these systems are based upon changing the voltage applied, the torque characteristics correspond primarily to those of armature-control, namely constant torque, and an output varying directly with the speed, (although for the intermediate speeds secured by field weakening, the available power is constant between voltage steps). The system is therefore particularly suited to loads whose power demand varies with the speed. When the load has this characteristic the intermediate speed-steps may with advantage be adjusted by means of a resistor in the armature circuit. It is apparent that for the control of compound-wound motors driving machines which do not require close speed-regulation, such an arrangement is especially well adapted.

Where the machines require constant power at all speeds a multiple-voltage system with voltages varying from 60 to 250, must carry, on the low voltage, current over four times as great as that necessary for the same horse-power at 250 volts. The result is excessive loss of energy in the line wires, poor regulation of the motor and large losses in the motor. The loss due to brush drop is in itself a considerable item on the low voltage. Suppose a five horse-power 220 v. motor has a brush contact drop of 1 1/2 volts; the loss will be say 20 amperes times 1 1/2 volts which equals 30 watts. Now

assume a multiple-voltage motor, with the same brush drop, delivering the same power and we have about 80 amperes on the low voltage step, which means a loss of 80 times 1 1/2 or 120 watts. This assumes the same drop, and not the same brush contact resistance. If the resistance were the same in both cases, the drop would be nearly four times as great on the low voltage as on the high. The efficiency, under these conditions, is necessarily lower than would be the case with field control. When the motor is operating at full-load armature current, the voltage is very low, and at the time normal voltage is reached, the motor is running at 1/4 load or less.

It is an important advantage of the multiple-voltage system that absolutely standard motors, the same as are used for constant speed duty, can be used with entirely satisfactory results throughout the speed-range of the system, provided of course, that the rating of the motor be reduced in the same ratio as the voltages employed.

In the evolution of multiple-voltage, several different combinations of voltages have been employed. The first system was devised by H. Ward Leonard,* who used three generators of 62, 125 and 250 volts respectively, connected as shown in Fig. 7. The motor fields were connected across the 250 volt line while the armatures were connected in turn to the several voltages indicated on the diagram. If the voltages are plotted as in Fig. 8, it is seen that the increments are not uniform throughout; as would be indicated by a straight line, but a jump is caused at 250 volts by skipping the 312 volt step. This step could not be obtained from the combination of 62 and 250 volts,

*United States Patent No. 478, 344, July 1892.

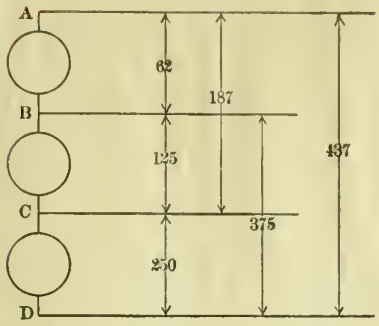

Fig. 7. Ward-Leonard Multi-Voltage System –

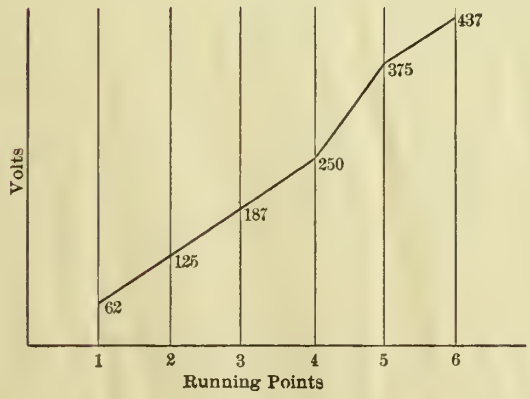

Fig. 8. Ward-Leonard Multi-Voltage System –
Voltage Steps

since such a combination would short-circuit the generator BC. With this exception the scheme gave an arithmetical progression of voltages.

Crocker-Wheeler System. By adopting another arrangement of voltages, the Crocker-Wheeler Co., developed a system which gives a strictly straight line speed curve, the speeds increasing in arithmetical progression throughout the range, in steps of about 40 volts.

The combination by which the six voltages are obtained will be made clear by reference to Fig. 9, which shows the arrangement of this form of the system when 240 volts is used for the total voltage. The standard pressure employed at the terminals of the motors is 230 volts across outside wires, which reduces the six voltages to 38, 77, 115, 153, 192, and 230 volts respectively. The lowest voltage is not ordinarily used as a running step in the speed range, but serves merely as a step in starting. The intermediate speeds, between the voltage steps, are obtained by field control, although resistance in the armature circuit may be used if the character of the load makes it desirable. The drum type controllers used with this system are so arranged as to throw into circuit a suitable armature resistance at the time of changing voltage, and a dash-pot device short-circuits this resistance automatically when its purpose has been accomplished.

Using a 10 h.p. motor by way of example, Crocker and Arendt* have given the following table to illustrate the speeds and efficiencies at the several speed steps, assuming constant rated-torque.

*Electric Motors : Their Action, Control and Application by F. B. Crocker and M. Arendt.

TABLE II.

Terminal Volts	Watts Input	IR Drop in Arm. & Brushes	C.E.M.F.	Speed R.P.M.	Watts Output	Effic. %
40	1710	11.8	28.2	106	971	56.6
80	3190	11.8	68.2	258	2370	74.2
120	4670	11.8	108.2	409	3750	80.1
160	6150	11.8	148.2	560	5150	83.5
200	7630	11.8	188.2	711	6530	85.6
240	9110	11.8	228.2	862	7920	86.7

This shows a range of speed of 1 to 8 by voltage control; counting the lowest voltage as a running step.

The speed-regulation of the same motor is shown to be as follows, (the regulation by rheostatic control being also given for comparison).

TABLE III.

Controller Notch	Multi voltage			Rheostatic Control		
	R.P.M. Rated Torque	R.P.M. No load	% Regulation	R.P.M. Rated Torque	R.P.M. No load	% Regulation
1	106	145	13.7	106	854	705.0
2	258	296	11.5	258	865	235.0
3	409	447	9.2	409	875	114.0
4	560	599	7.0	560	883	48.4
5	711	750	5.2	711	892	25.2
6	862	910	4.6	862	910	4.6

Bullock System: The most logical arrangement of speed steps is that of a geometrical progression, in which each increase of speed is a certain percentage increase rather than

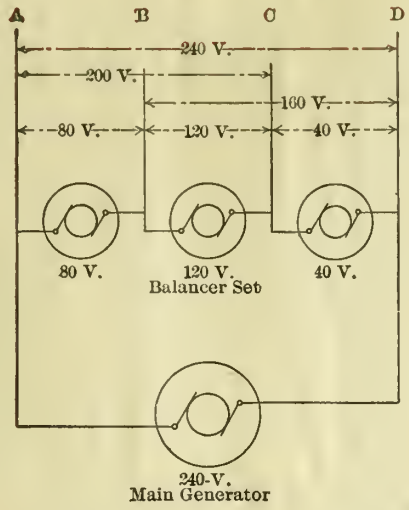

Fig. 9. Crocker-Wheeler System

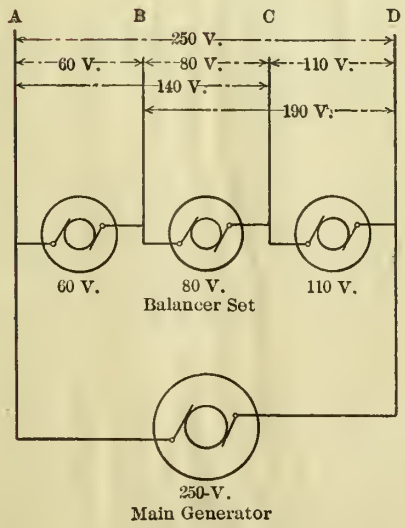

Fig. 10. Bullock System

an increase by a fixed amount. In order to have a geometrical progression with a four-wire system, a factor, r, must be chosen which will fulfill the following conditions, where (a) is the lowest voltage;

$ar^3 = a + ar$, $ar^4 = ar + ar^2$, and $ar^5 = ar^2 + ar^3 = a + ar + ar^2$.

(The voltages available being; a, ar, ar^2, ar^3, ar^4, and ar^5).

These conditions will be satisfied when r = 1.3247; that is, if each voltage is 32.47% higher than the next lower voltage, the geometrical progression can be realized with four wires. For example, three voltages of 60, 79.5 and 105.3 respectively would satisfy the conditions.

The Bullock Electric and Manufacturing Co. developed a commercial system in which 60, 80, and 110 volts were adopted as being near enough to the theoretical values. The available voltages on this basis are 60, 80, 110, 140, 190, and 250 obtained by the combinations indicated in Fig. 10. The three machines of the balancer set have voltages of 60, 80, and 110, each voltage being practically 1/3 greater than the preceding. The resulting speed range, by voltage control alone, is about five to one. The following table, also taken from Crocker and Arendt's "Electric Motors" shows the speeds for the 10 h.p. motor previously cited. Rated full-load torque is assumed at all speeds.

TABLE IV.

Terminal Volts	IR drop in Arm. and brushes	C.E.M.F.	Speed R.P.M.	% increase step to step
60	11.8	48.2	182	---
80	11.8	68.2	258	42
110	11.8	98.2	374	45
140	11.8	128.2	485	30
190	11.8	178.2	673	39
250	11.8	238.2	900	34

This range is usually supplemented by moderate field weakening (about 33%) above the highest voltage step, thus increasing the total speed range to approximately 6 1/2 to 1.

The intermediate steps, between voltages, may be obtained either by armature or field control, the latter being more generally employed. The controller is of the drum-type and gives speed steps of about 7% each. No external resistance is used in the armature circuit at the transition points between voltages as with these increments of speed, it is found to be unnecessary.

VARYING VOLTAGE BY AUXILIARY MOTOR-GENERATORS.

Of the schemes involving a separate motor-generator set for each motor, three which have been commercially developed, will be described. All are alike in the essential feature of supplying the power-motor from a variable voltage generator, a separate motor-generator set being required for each motor so operated. On account of their cost and complication, the practical applications of these systems are limited to very special

conditions. They have been successfully employed in the operation of large newspaper printing presses, the turning of gun-turrets on battle-ships, and the driving of large rolls in steel mills.

Ward-Leonard Motor-Generator system.* The simplest application of this principle is shown in Fig. 11. The variable speed or "working" motor, WM, has its field connected directly to the constant voltage supply mains, but its armature is fed through an independent circuit from an auxiliary generator D, which is driven by a constant-speed motor M. The latter is connected to the supply mains and operated as any other constant-speed motor, its function being simply to drive the generator, D, at constant speed. The voltage of the generator is varied by field control through the agency of the field rheostat, R, which is so proportioned as to reduce the voltage from maximum to zero by gradual steps. This gives motor speeds from zero to normal in one direction. The reversal of the motor is accomplished through the reversal of the generator voltage, by reversing its field connections as the controller is passed over the zero position. Both machines of the generating set must be somewhat larger than the working motor, since each must carry the entire load, plus losses in the working motor and auxiliary generator respectively. The exceeding flexibility and nicety of control of such an equipment are at once apparent. The speed regulation is fairly good even at the slowest speeds so that a machine may be "inched" along or run very slowly without the jerks or irregularities of speed which accompany varia-

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* United States Patent No. 463,802, Nov. 1891.

tions of torque with armature rheostatic control.

Another advantage is to be found in the fact that the heavy motor current required to start high-torque loads is supplied at the minimum possible voltage. The line and generating station are thereby relieved of the abnormal draught of power which, by rheostatic control, would be wasted in the rheostat at the time of starting.

Although its excessive cost precludes the general application of such a system, its special characteristics have brought it into use on battleships, for the operation of gun-turrets, where wide range and fine adjustment of speed are essential. In steel mills, it has proven a successful method of driving large rolls, a flywheel being in this case an important part of the motor generator set.

The Boost and Retard System is a modification of the preceding scheme. It reduces the first cost of equipment by reason of the smaller motor-generator set, which in the present system need have only about one half the capacity of the "working" motor. The auxiliary generator does not supply the entire power, but is connected in series with the working motor, as shown in Fig. 12, and serves as a "booster" or "reducer" of the line voltage. The normal voltage of this generator is equal to that of the line, so that it will double the line voltage when used as a booster and will annul the line voltage when used as a reducer, i.e., when opposed to it. By this means the voltage at the working motor, W.M., is varied at will from zero to twice the voltage of the line. With a distributing system of 110 volts, a 220 volt working motor would be used.

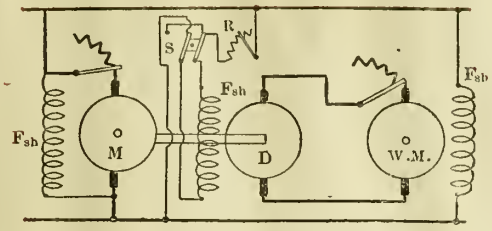


Fig. 11. Ward-Leonard Motor-Generator System

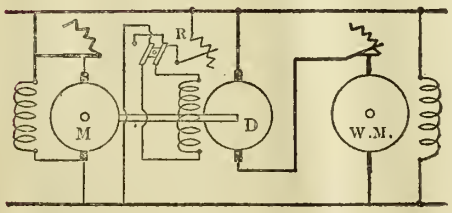


Fig. 12. Boost and Retard System

The e.m.f. of the generator D is controlled by variation of field resistance and is reversed by reversal of the field connections through the operation of a special reversing device in the field controller, the field having first been gradually reduced to zero. When the motor generator set is opposing the line voltage the functionsof the two machines are automatically reversed. The generator D becomes a motor, (its counter e.m.f. opposed to the line), driving the motor M as a generator and causing it to send current back into the line to supply part of the energy used by the load motor.

The reversal of the power motor cannot be accomplished, as in the last method, by reversing the generator e.m.f., but must be taken care of by reversal of armature connections of the power motor itself.

Since the ampere rating of the generator D is the same as that of the power motor while its voltage is only half, the watt rating is one-half of that required by the load motor. Thus the motor-generator set is about half as large as that required in the preceding system.

The efficiency of this and the last described method is, of course, impaired by the losses in the auxiliary machines, but will nevertheless average much higher than with rheostatic control.

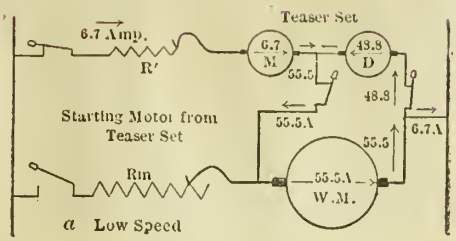
Teaser System. Another arrangement, developed by the Bullock Company especially for the operation of rotary printing presses, employs the motor-generator set only for supplying low voltage to drive the working motor at the very slow speeds required for making ready the press and threading in the web. At these speeds the power consumed is comparatively small so that

a small generator-set or "teaser" may be used. The higher running speeds are regulated by armature rheostatic control of the working motor. The essential features of the scheme will be understood by referring to Fig. 13.

The function of the teaser-set is in reality that of a current-transformer. It takes a small current at line voltage into the motor-end and delivers a large current at low voltage from the generator-end. The working motor is by this means supplied with sufficient current to overcome the torque of the load, and at a voltage only slightly greater than the IR drop in the armature circuit, so that only a small counter e.m.f. is required to be generated by the working motor and it runs at very slow speed. The working motor is gradually speeded up, by increasing the voltage of the "teaser" generator, (this being done by speeding up the motor M, either by armature or field control), until the speed of the power motor is such that it can be accelerated by armature resistance, on the full line voltage, without serious irregularities of speed. The teaser set is then cut out of circuit and the main motor is thrown on the line through the resistance Rm.

A later modification of this method, employs a compound-wound teaser generator which is found to give better results, as the former equipment was sometimes stalled by sticking of the press. The compounding serves to raise the voltage at such times and thus to insure sufficient current to develop the additional torque for carrying the press over the sticking point.

An important advantage, in addition to the smooth running at low speeds, obtained by this method is to be found in



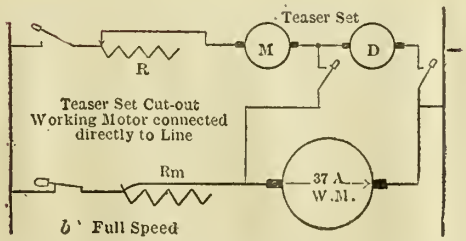


Fig. 13. Teaser System.

the great saving of power, over that required by resistance control. By the latter method the large current necessary for starting and slow running must be supplied at line voltage, involving a loss in the rheostats many times greater than the useful power.

VARIABLE SPEED BY CHANGING FIELD MAGNETIZATION.

It has been shown that an increase of the field flux, ϕ, will decrease the speed, and a weakening of the field will cause the speed to increase. The weakening of a motor field reduces the full load torque, but by reason of the accompanying increase of speed, the power developed remains practically constant as pointed out in table No. VI. All field-controlled motors are therefore inherently constant power and not constant torque machines. For the most important class of variable-speed work in shops, this is the desired characteristic.

The variation of the field magnetism is most readily accomplished by means of resistance in series with the shunt field winding of the motor, but the result is also obtained by varying the reluctance of the magnetic circuit in at least two commercial designs, which will be later described.

The method of shunting part of the field current is used for cutting out the series winding of compound motors in elevator service, and it may be used as a means of weakening the field of series motors.

Shunt Field Control (With Standard Motors). The insertion of resistance into the shunt field circuit affords the simplest and most easily controlled of all methods of speed variation. The efficiency is very satisfactory at all speeds, since the additional resistance in the field circuit does not introduce an additional loss. As a matter of fact the I^2R loss in the field circuit, is reduced by the insertion of resistance, because of the reduction of field current while the total voltage remains constant. There are other losses however- windage,

friction and commutation losses- which cause the efficiency to drop somewhat with increase of speed through any considerable range.

This method of speed control has its chief limitation in sparking at the commutator. The current varying in the short-circuited armature coil generates an e.m.f. of self-induction to oppose the change, and this opposition must be completely neutralized to insure perfect commutation. To attain this result it is necessary that each armature coil, which is connected with the commutator segments passing under the brushes at any given instant, shall be at that same instant moving through a magnetic field, called the "commutating field", the polarity, intensity, and area of which are such as to develop an e.m.f. just sufficient to arrest the current in the coil and build up a current of the same strength in the opposite direction during the time the coil is short-circuited by the brushes.

For any particular armature current, and any particular strength of motor field, within certain limits, it is possible to find a suitable commutating field in the magnetic "fringe" somewhere between the poles of the motor. But any variation of either armature current or field magnetism will cause a shifting of the resultant field, so that the magnetic fringe will no longer remain suitable, in value or location, for sparkless commutation.

In the present type of variable speed motor we have both of these quantities changing; the armature current varying with the load, and the strength of field varying inversely with the speed. The reactance of the armature coil also varies with the speed, but fortunately the rate of cutting the lines of

force of the commutating fringe varies in the same ratio thus automatically taking care of this characteristic provided there is a magnetic fringe which can be utilized.

The effect of armature reaction upon the field distribution of a standard constant speed motor is to produce a shifting or distortion of the main field, the effect becoming greater as the load is increased. If the motor field be weakened to produce higher speed, while retaining the same load, the effect of armature reaction will be increased, and if the field weakening be carried far enough, the motor field may be so far distorted as to reduce the flux to zero under the leading pole tip as illustrated in Fig. 14. If the brushes are given a backward lead the armature reaction has also a demagnetizing component which further weakens the main field.

The distortion which takes place at high speeds on weakened field is more clearly shown in Fig. 15 which gives the field distribution curves at the maximum speed of a motor of standard construction having a speed range of 4 to 1. The solid line shows no-load and the dotted line, full-load distribution. The dotted line shows that, in this motor, the zero point, A, is well under the pole tip. At the point midway between poles, where the brush is indicated, the magnetic fringe is the reverse of the polarity desired for commutation. Consequently no assistance can be had from the fringe at the high speeds and at full load. At the lower speeds the fringe will assist in commutation, if the brushes are shifted backward. A motor which has its brushes shifted from the central point, will not be reversible, unless the brushes are shifted to correspond to the direction of rotation each time the motor is reversed.

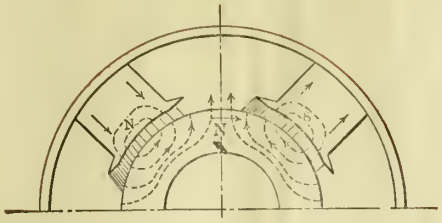


Fig. 14.

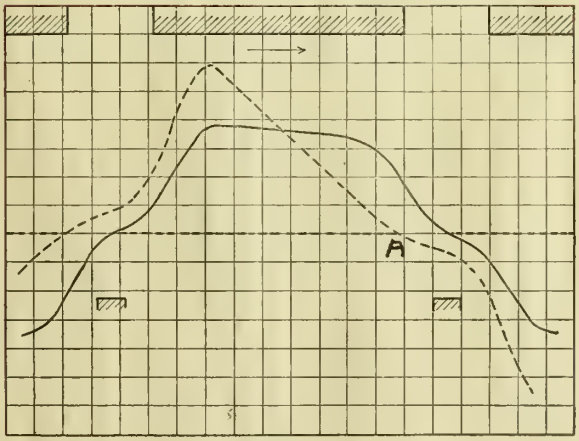


Fig. 15.

It may be noted here that moving the brushes backward will shift the resultant field of the motor in the same direction, though of course not in the same amount as the brush shift.

Another feature, which is unfortunate for the designer, is the fact that variable speed motors with a wide speed-range must have a rather low minimum speed in order that the maximum speed may not exceed good practice; and low speed calls for a large number of turns in the armature winding, which, if obtained by using many turns per coil, will produce a high reactance, and if by increasing the number of coils and commutator bars, will increase the cost.

To overcome the commutating difficulties the designer so proportions his variable speed motor that it will have a strong field and a comparatively weak armature. Too small an air gap between the armature and pole faces will provide a path of low reluctance for the cross magnetism of the armature and will thus increase the armature reaction. Therefore a stiff magnetic field is provided by using a large magnetizing force and a wide air gap. The resistance property of the carbon brush is relied upon to a certain extent for communication, as it will permit of considerable variation in the commutating conditions. Other features of a variable speed design for a standard type of motor are; large frame to take care of the large total flux, large number of coils and few turns per coil in the armature to keep the self-induction per coil as low as possible; and a correspondingly large number of commutator bars. Motors thus designed will naturally be somewhat more expensive than motors of the same rating for constant speed service.

High flux density at the pole tips tend to prevent

distortion of the field and thus aids commutation. The Storey motor, formerly manufactured by the Magneto Electric Co., employed this device in combination with an armature winding of many sections. The flux was concentrated at the pole-tips by making the poles hollow as shown in Fig. 16.

The speed increase that can be obtained by field weakening from the standard shunt motor, not specially designed for variable speed, will probably average about 30 percent, though some motors will not stand this increase at full load without objectionable sparking. Evidently by reducing the rating of such a motor, its speed range can be increased. An approximate idea of the ratings thus permitted can be had from Table V, although the exact rating permissible for a given motor depends upon the excellence of its design with regard to sparking, and varies largely with different machines.

TABLE V.

Frame size	Ratings for Variable Speed 2:1 Range	3:1 Range
3	2 H.P.	1 1/2 H.P.
10	7 1/2	5
15	10	7 1/2
20	15	10

In summing up this method of control it may be said that the single voltage system with shunt field controlled motors is almost the ideal of simplicity and efficiency and gives the best possible speed regulation. Where the range of speed must be greater than can successfully be covered with the standard type of motor, the difficulties may be overcome by compensated

motors or motors of the "interpole" type, which will be hereafter described.

The Thompson-Ryan Compensated Motor. The essential features of this variable speed motor are outlined in Fig. 17.

Between the polar projections c and d, there is a "balancing ring" made up of sheet steel laminations,- h, i, r, and e e, f f. The last named pieces constitute extensions of the polar cores. The portion of the ring opposite each interpolar space contains two coils. One coil j j embraces the small core r, while the other and larger coil k k, embraces one of the e and one of the f cores. These coils are all connected in series with the armature, so that the current they carry is always equal to that of the armature. The compensating coils k k are connected in such manner that the current in their conductors is opposite in direction to the current in the armature conductors lying directly under them. These equal and opposite currents neutralize each other, so that with proper proportions the reaction of the armature upon the field may be entirely neutralized. Under these conditions the distribution of the field magnetism remains unchanged, no matter how weak the field may be or how strong the armature.

The smaller coil, j j, which is wound upon the core r, develops a magnetic flux which serves as the commutating field. This coil is in series with the armature, and therefore the flux developed by it rises and falls with the rise and fall of the armature current thus producing the condition that is needed for perfect commutation. It is in effect a commutating pole having precisely the same action as an "inter-pole", with the exception that in the present design the path of the commutating

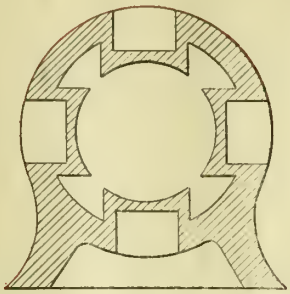


Fig. 16. Hollow Poles of Storey Motor.

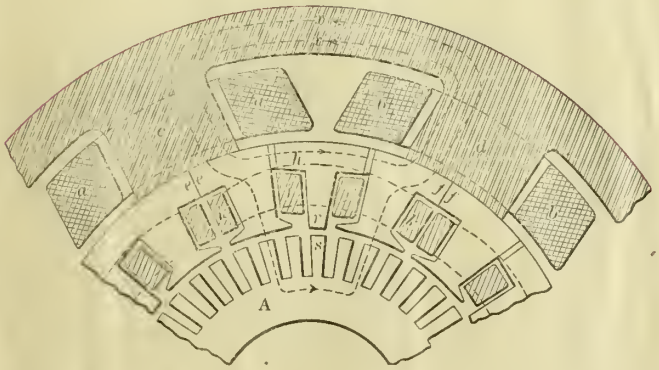


Fig. 17. Thompson-Ryan Compensated Motor

pole flux is through the "balancing ring", h, i, and not through the main yoke as in the interpole motor.

By the means described a suitably varying commutating field is not only provided but the armature reaction is also neutralized and the main field thereby maintained in its normal proportions under varying load and varying speed. In practice, the degree of perfection depends upon the accuracy with which the electrical and magnetic parts are proportioned.

These motors are regularly manufactured in sizes from 3/4 to 50 horse power and with variable speed ranges of 6:1, 5:1, 4:1, 3:1 and 2:1. They are usually six-pole designs.

Inter-pole Motors. In order to overcome the sparking difficulties inherent in the field-controlled motor of the standard type, variable-speed motors may be equipped with "commutating poles". This type of machine is in a general way an ordinary shunt motor with the addition of a small auxiliary pole midway between each pair of main poles. The function of the auxiliary poles is to produce and maintain a magnetic field, independent of the main field of the motor and suitable in strength and location for proper commutation under all conditions of load and speed. This means that the electro-motive force generated in a short circuited armature coil, by the interpole flux, must be of just the proper value to arrest the current and reverse it in the coil, while the terminals of the coil are passing under a brush, i.e., it must just balance the reactive voltage of the coil. The reactive voltage ($2\pi fLI$) varies directly with the reactance and with the current in the coil. If we regard the inductance, L, of the coil as constant,* the reactance will

*Inductance is not strictly constant with varying current,

vary directly with the speed of the armature. Hence the reactive voltage varies directly with speed and armature current, and in order to counteract this voltage at all times, the e.m.f. generated by the auxiliary pole must vary with the same factors. Since the e.m.f. generated by the field of the auxiliary pole varies directly with speed and flux density, it is evident that the desired result will be produced if flux density of the inter-pole be made to vary with the armature current. To meet this requirement, the inter-pole windings are connected in series with the armature.† It has been found good practice to work the iron of the inter-pole at such a place on the magnetization curve that the saturation point will be reached with about twice the normal armature current. This being well beyond the proper operating load of the motor, it is seen that through the normal working range, the magnetization curve approximates a straight line closely enough for very satisfactory results. The resistance qualities of the carbon brush, as an aid to commutation, easily take care of any slight departure from the theoretically correct value of inter-pole flux.

The arrangement of poles and windings is shown in Fig. 18 in which the armature is shown removed from the motor and represented by A. The motor is reversible by means of the reversing switch, S, which merely reverses the armature current without affecting the polarity of the main fields.

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because of the effect of saturation in the iron.

†The inter-pole flux is not <u>strictly</u> proportional to armature current because of the effect of saturation, but it is not wanted strictly proportional because reactance of short-circuited coil is not strictly constant, as previously pointed out.

Since the inter-pole windings are connected permanently in series with the armature, the reversal of the motor, by reversing the armature current, also reverses the polarity of the inter-poles, thus producing the required change in polarity of the commutating field without any change in the brush position.

It will be remembered that the field set up by the armature is opposite in direction to that desired for commutation, and to overcome this field and produce one in the right direction it is necessary for the inter-pole to be energized by a greater number of ampere-turns than the ampere-turns on the armature. Thus a certain constant number of the turns on the inter-pole may be regarded as serving only to balance the armature flux, under whatever condition of load, and the surplus turns above that number are the ones which produce the resultant commutating field.

The result of the independent commutating field is a machine which can be operated as a motor or generator, for either direction of rotation, without shifting the brushes or changing the connections. The brushes of the motor are set permanently in a central position, opposite the commutating poles. The inter-poles do not prevent the distortion of the main field by armature reaction. The distortion takes place, and becomes greater as the field is weakened to increase the speed, the same as in motors of standard construction, but this shifting of the field does not affect commutation, because the required commutating field is independently taken care of. A comparison of Figs. 19 and 14 will more clearly illustrate the action. In Fig. 19 the inter-pole flux is seen to be opposed to the armature flux

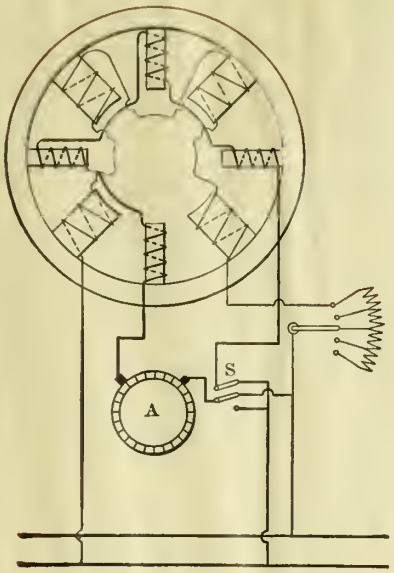

Fig. 18. Inter-pole Motor

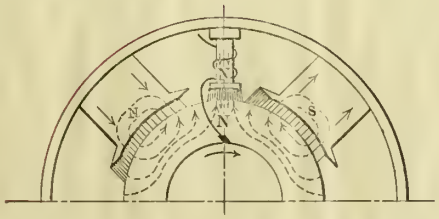

Fig. 19. Inter-pole Motor

Mr. C. H. Bedell,* in a paper before the American Institute of Electrical Engineers, has presented curves showing the field distribution of a 5 h.p. inter-pole motor having a speed range of 275 to 1100 r.p.m. The curves for minimum speed are shown in Fig. 20 and those for high speed in Fig. 21.† In each case the solid line is the no-load and the broken line the full-load curve. The slow speed test shows very little armature reaction but the test at high speed shows such excessive reaction under full load conditions that the polarity of the weakened pole at the right hand corner, is not only neutralized but is actually reversed by a considerable amount. It will be noted, however, (Fig. 21) that the curve is brought back to the proper polarity in the commutation zone by the action of the interpole.

It is stated in the paper referred to that the change in relative amounts of iron and copper in the armature, made possible by inter-pole construction, increases the efficiency on light loads while the full load efficiency is not much altered, the result being a somewhat better "all day" efficiency than that of standard type motors.

A remarkable feature of this design is its peculiar speed regulation. If the brush is shifted away from the center of the inter-pole flux, the latter has a slight compounding effect upon the motor. When the brush is shifted to one side this compounding is cumulative; when shifted to the other side,

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*T. A.I.E.E. Vol. 25, p. 329, "Direct Current Motor Design as influenced by the Use of the Inter-pole".

†Fig. 21 has been slightly modified to embody results brought out by Mr. H.F.T. Erben in the discussion of Mr. Bedell's paper.

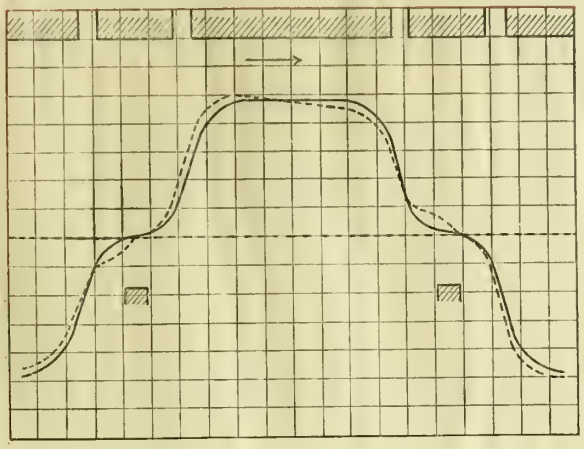

Fig. 20.

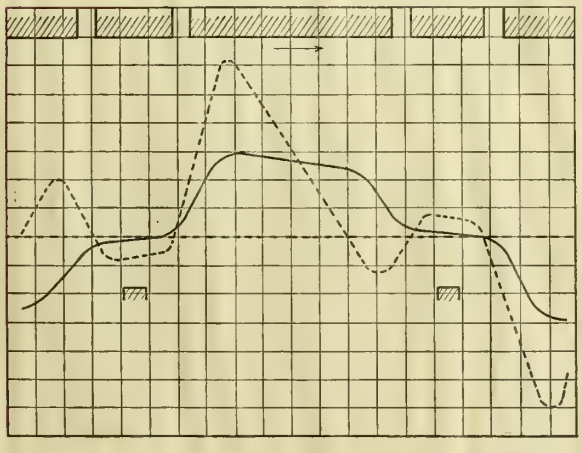

Fig. 21.

the compounding is differential. For a given speed, (that is, for a given strength of the shunt field), it is possible to find a brush position which will insure practically constant speed at all loads. At higher speeds, (weaker shunt field), the differential effect is greater and the speed will increase somewhat with the load; at stronger field the speed will decrease with increase of load. This characteristic is illustrated in Fig. 22 which shows a set of speed curves of a motor built by the Electro-Dynamic Co. of Bayonne, N.J.

CHANGING RELUCTANCE OF MAGNETIC CIRCUIT.

Ohm's law for the magnetic circuit shows another possibility. The flux may be varied, without changing the magneto-motive force, by varying the reluctance of the magnetic circuit. Since it is impossible to change the permeability of any magnetic material, the reluctance can be changed only by mechanical movement of the iron parts, so as to change the length or area of the air portions of the circuit.

In one of the early methods, due to Edison, this result was produced by means of a wedge of iron which could be withdrawn to decrease the amount of metal in the yoke, thus reducing the total flux. This method was originally intended for generators. It did not provide means to overcome sparking and is not in commercial use at present.

Another scheme, the Diehl variable reluctance method, comprised a hinged yoke, so constructed that the two pole-pieces of a bipolar machine could be closed in upon the armature or opened away from it like a pair of calipers. The air gap between armature and poles was thus varied. This also, was originally

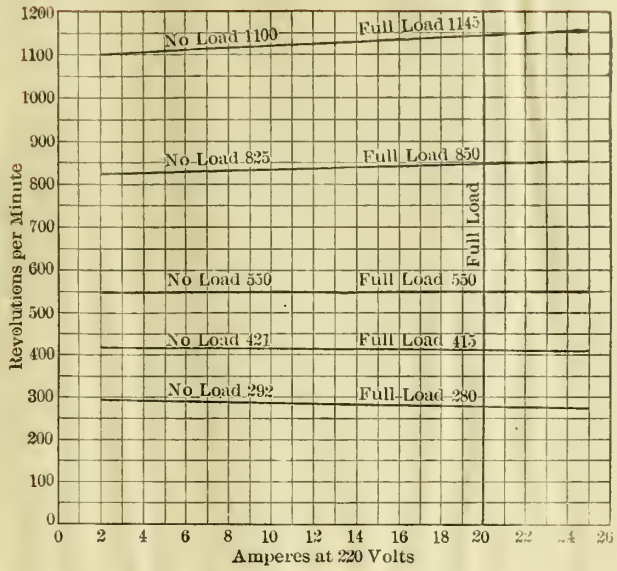

Fig. 22.

The Speed Curves of an Inter-pole Motor

intended for generators, but seems not to have been very successful. More modern and successful methods have been developed by at least two American manufacturing companies; one depending upon a radial movement of the poles, the other upon a longitudinal shifting of the armature.

Moving Poles Radially. The Stow Multi-speed motor,* manufactured by the Stow Manufacturing Co. of Binghamton, N.Y., is dependent for speed variation upon one of these methods of varying the reluctance of the magnetic circuit. Both the field current and e.m.f. impressed upon the armature are maintained at a constant value, the armature and field windings being directly connected to the line during the operation of the motor. The method of varying the field magnetism is by mechanically moving the pole-cores radially with reference to the armature. Each pole-piece consists of two parts, a solid cylindrical core or "plunger" A, and a cylindrical shell, B, surrounding the core as shown in Fig. 23. The pole-shoe is an integral part of the hollow shell, B, and the gap between this shoe and the armature is unchangeable, the shell being rigidly connected with the motor frame. The solid core, A, is free to slide within the outer shell, thus varying the reluctance of the magnetic circuit. When the core is in contact with the shoe-end of the shell, the magnetic circuit has its minimum reluctance, and under this condition the motor runs at its normal or slowest speed. As the core is gradually withdrawn, the speed increases, due to the weakening of the field. In some of the larger motors the pole plunger extends entirely through the pole pieces so that its inner end forms a

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*U.S. Patents Nos.666,315 and 672,419, January and April, 1901.

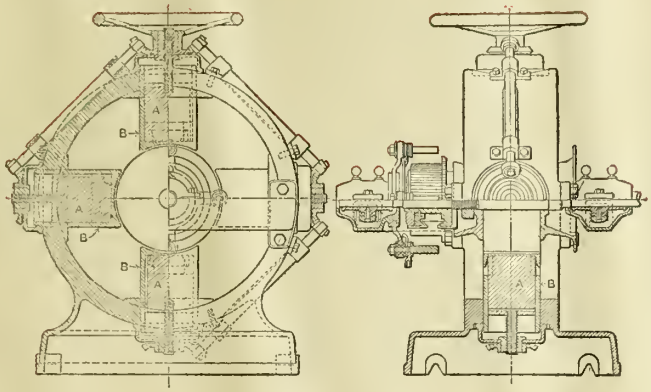

Fig. 23. Stow Multi-speed Motor

part of the polar surface.

The design of the pole-piece and its plunger is such that, as the total magnetic flux is diminished by the outward movement of the plunger, the remaining flux is forced more and more through the pole-tips, thus tending to maintain at all speeds, a commutating field of sufficient intensity to insure sparkless commutation. It will also be observed that as the plunger is being withdrawn, the air column within the pole-piece offers a gradually increasing barrier to the cross magnetizing effect of the armature current, until when the field strength is reduced to minimum by the reluctance of the air column, the armature reaction is also reduced to a minimum through the same cause.

A hand-wheel on the top or side of the motor frame is arranged to move the pole cores in or out by means of screws rigidly attached to the pole cores and passing through threaded gear-wheels. All the poles are moved simultaneously by the one hand-wheel. Because of the nature of the control, it is plain that there are no distinct "steps" in the speed variation and it is possible to obtain any speed desired within the limits of the motor. This refinement of speed adjustment is perhaps the most unique operating feature of the design. The total elimination of any electrical controlling device, other than an ordinary starter, is a noteworthy feature though one not adapted to remote control. The standard speed-range of these motors, as manufactured by the Stow Mfg. Co., is one to three, or a maximum increase of 200%.

<u>Moving the Armature Longitudinally</u>. The Lincoln Variable Speed Motor is another design depending upon variation of re-

luctance of the magnetic circuit for speed control.* The general construction of this motor, as manufactured by the Reliance Electric and Engineering Co., is shown in the vertical longitudinal section, Fig. 24. The armature is moved in and out longitudinally between the pole pieces. As the armature is withdrawn the area covered by the poles is decreased; and in addition to this, the armature is slightly tapered so that the length of air gap is increased simultaneously with its decrease of area. Thus the variation of length of gap is combined with the variation of magnetic area to produce the desired change of flux. Although the increase in length of air gap has a tendency to "stiffen" the magnetic field, this feature is not relied upon to prevent sparking at the high speeds. Small commutating poles are provided in such positions that the armature is brought gradually under their influence as it is shifted away from from the main poles. The windings of the commutating coils are connected in series with the armature, for the reasons explained under "Inter-Pole Motors".

The method of mechanically shifting the position of the armature is clearly shown in Fig. 24. The armature shaft runs in two bearing sleeves; the one at the commutator-end of the motor is free to slide axially but is restrained from turning in the yoke or bearing bracket. In this sleeve is mounted a ball-bearing which receives the entire end-thrust caused by the displacement of the armature in the magnetic field, as well as the radial load on that end of the shaft. This thrust-bearing box, carrying with it the armature and the brush rigging, is moved in

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* U.S. Patent No. 829, 974, Sept. 1906.

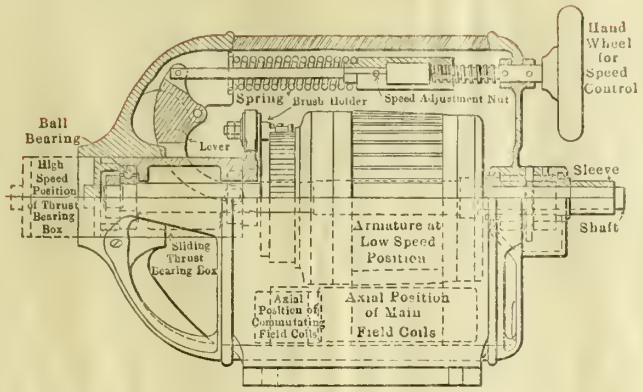

Fig. 24. Lincoln Variable Speed Motor.

and out by turning the hand-wheel at the rear end of the motor. The threaded shaft of the hand-wheel turns in an adjustment nut and thus operates a lever to shift the bearing box. In order to reduce the effort necessary to turn the hand-wheel, a helical spring is provided to balance the end-thrust of the armature due to its magnetic pull.

The bearing sleeve at the pulley- or pinion-end of the motor turns with the shaft but suitable collars prevent it from sliding through the bearing; it thus forms a hollow journal through which the shaft is free to slide, and upon which the pulley or pinion is mounted.

These motors are built for speed ranges as high as 10 to 1, and for reversible operation under all conditions. In this, as in the Stow design, the principle of control renders an infinite number of speed steps available within a given speed range and no electrical controller, other than an ordinary starter, is required.

Shunting Part of Field Current. This is another method by which the field flux may be varied, but it is not adapted to shunt motors, the same result being attained more economically by resistance in series with the field windings. The method is, however, of considerable importance for weakening the fields of series motors and for cutting out the series fields of compound motors after they have been brought to speed. The latter application is quite extensively used for the control of motors operating passenger elevators. The heavy torque requirement at starting is met by the compound winding and the constant speed requirement, when running at full speed, is realized by short-circuiting the series field.

CHANGING NUMBER OF ACTIVE ARMATURE CONDUCTORS.

Since the speed of a motor must be such that its rate of cutting flux is just sufficient to generate the impressed voltage, (minus the IR drop in armature), and since this total rate of cutting depends upon the number of armature conductors in series, as well as upon the velocity, it becomes apparent that changing the number of active conductors will cause a change in speed.

There are two possibilities for making this change while the motor is in operation, first, by using an armature having two or more windings each connected with a separate commutator, and second, by changing the number of field poles (without changing the total flux) at the same time changing the number of conductors in series by disconnecting certain of the commutator brushes.

Double Commutator Motors. In order to vary the number of armature conductors, which add their counter e.m.f.'s in series between the motor terminals, it is common practice to use two separate armature windings in the same slots, and a commutator at each end of the armature. The motor has one field frame and one field winding which may be either shunt or compound as in machines of the ordinary design.

The two armature windings may be identical, or they may have a different number of turns. If they are alike (as in the C. & C. and G.E. Co. systems*) they are run in series for the low speed and in parallel for high speed; such a "series-

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* U.S. Patent No. 757, 394 April 1904.

parallel" control gives two fundamental speeds on a single-voltage system without the use of a resistor in either armature or field circuit. The speed for one winding alone or for both in parallel will be twice the speed obtained when the two windings are in series.

If the two armature windings are unlike (as in the Commercial Electric Co. system), they are run in series for the lowest speed, and two higher speeds are obtained by running each winding singly, while a fourth still higher speed is sometimes secured by electrically opposing the two windings in series. By this method three or four fundamental speeds are available.

For either of these two classes only one line-voltage is necessary. The intervening speed steps, between those obtained by the change of armature conductors, are usually secured by shunt field control. A resistor in the armature circuit may be used in some cases. The total speed range is commonly 4 to 1, with the speed steps arranged in geometrical progression.

C. & C. Electric Company System. The C. & C. series-parallel system has been used principally for the operation of large printing presses, though also adapted for driving other kinds of machinery.

The motor for printing press service is of the ordinary slow-speed, compound type, with the exception that it has two commutators and two separate armature windings on the one armature core. The two armature windings are exactly alike, so that they may be run in parallel, and the speed variation is obtained by running them first in series and then in parallel; they are not run separately. The field windings are so arranged that the series coils can be cut out after starting, thus securing the

advantages of a powerful torque with minimum current at starting, and the good regulation of a shunt motor when running.

Resistance is inserted in the armature circuit for all speeds between the two primary speeds, and for speeds below that obtained by the series connection of the armature windings. Shunt field control is used for the speeds above those of the parallel connection of the two armature windings.

The controller, though somewhat elaborate, is operated by one lever. When the armature connections are changed over from series to parallel, or vice versa, it is necessary to open the circuit, and an automatic solenoid switch of special design serves to make this change without the use of blow-out coils.

Where the system is used for large newspaper printing presses, it is provided with emergency switches which make it possible to stop the motor from various points about the press. The controller has no "off" position in the ordinary sense, but the opening and closing of the circuit is accomplished by a suitable solenoid switch automatically operated by the controller and also by the emergency switches just mentioned.

The motors are built with interpoles when the service is such as to require them.

Commercial Electric Company System. The system introduced by this company is of the second named class of double-commutator motors, i.e., those having two dissimilar armature windings which may be connected separately or in series, but are never run in parallel. The number of turns in the two windings are in the proportion of 2 to 3. If we call the number of turns in one winding 2X and the number in the other winding 3X, it becomes apparent that the following relative speeds are obtain-

able:

Two windings in series, opposed; X conductors effective; speed = Maximum.

The 2X winding alone; 2X conductors effective; speed = 1/2 Max.

The 3X winding alone; 3X conductors effective; speed = 1/3 "

Two windings in series, 5X conductors effective; speed = 1/5 "

Thus if we call the minimum speed 1, the other speeds will be 1.7, 2.5 and 5. For the intermediate speeds, field regulation is the method employed. By omitting the opposition, or maximum speed connections, it is still possible to produce a 4 to 1 speed range, using about 40% field control for the intermediate steps and 60% above the highest fundamental speed. With this arrangement the total range is divided into twelve steps in the controller.

James Clark, Jr., & Company's Motors. A double commutator motor for machine-tool and similar variable speed service has been introduced by James Clark, Jr., & Co. of Louisville, Ky. The two windings on the armature are in the proportion of about 3 to 5. For the slowest speed, these windings are run in series, and two higher speeds are obtained by running them singly. The intervening speeds are obtained by means of resistance in the shunt field circuit. The controllers are usually constructed to give 15 speeds in approximately geometrical progression.

The inherent speed regulation on varying loads is good, and the full load efficiency does not vary much at different speeds within the range, as the separate windings are designed for the voltages used.

The standard speed range of these motors is 4 to 1. If

the two windings in series give a speed of 1, the long winding alone will give 1.6 and the short winding alone 2.66. From 2.66 to 4 is an increase of 50% which is obtainable by field control. It is seen that the same or a slightly greater field range between the primary speeds, makes possible a practically uniform variation of speed from minimum to maximum.

Summary : In cases where two or more voltages are not warranted, and a wide range of speed is necessary, especially where the load is of a nature tending toward constant torque rather than constant power, a double commutator motor may be used with excellent results. When the series-parallel control is used the speed changes correspond to those of the three wire equal-voltage system. The double commutator motors have very good inherent speed regulation, i.e., speed is nearly constant at all loads. The advantages of operation on a a single voltage two wire system have been pointed out. The two commutators, because of first cost and the extra maintenance they involve are rather serious objections.

Changing Number of Poles. Although this method has not met with commercial success, it is worthy of mention here as illustrating a possibility which has been tried out. A system was at one time developed by the Bullock Co. in which the number of poles and the armature connections were simultaneously changed, in such a manner as to change the number of armature conductors in series between terminals without changing the total flux to be cut by these conductors. The change of connections by which this was accomplished with one commutator is indicated in Figs. 25 and 26 which show a four-pole frame with ring wound armature. In Fig. 25 the connections are normal; alternate brushes are

connected to the same terminal and the current in the armature takes the four paths indicated by the arrows. If there are n conductors on the armature, the number in series between terminals is $\frac{n}{4}$.

Fig. 26 shows two of the field poles reversed in polarity and two of the brushes disconnected from the circuit, while the other two brushes which were formerly both negative terminals have now been connected to the line as + and - terminals respectively. The result is a two pole motor having approximately the same total flux as before but with only two paths for current through the armature and consequently $\frac{n}{2}$ conductors in series between terminals. Since there are twice as many conductors in series, the speed is reduced to one half, with the same total field and the same terminal voltage.

By the same means an eight pole machine could be changed to a four pole and a two pole; a twelve pole machine could be changed to a six pole and a two pole; the speed obtained in each case being directly proportional to the number of effective poles.

The armatures of these machines were necessarily of the Gramme ring type, which was expensive to wind and uneconomical of copper, a larger field frame was required to provide sufficient cross section for the two-pole distribution of flux, and a somewhat complex device was necessary to make the change of connections. The regulation was very poor on low speeds and the motor lost its torque, thus giving trouble when the poles were changed.

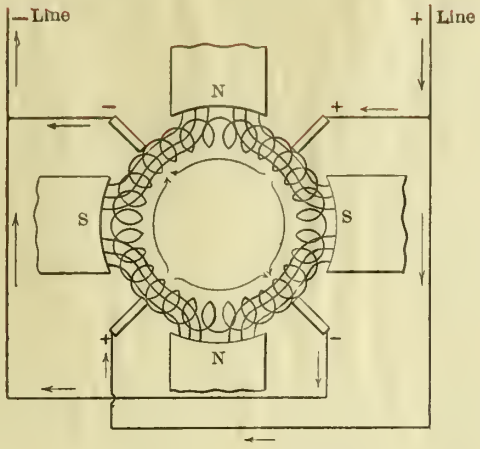

Fig. 25.

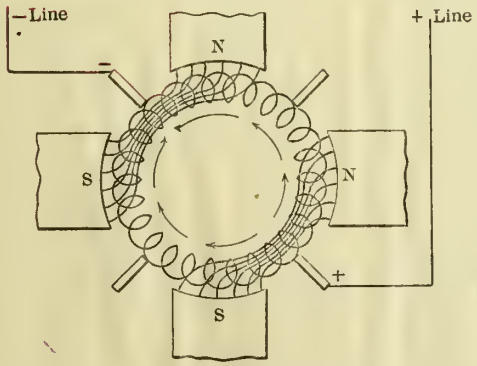

Fig. 26.

COMBINATION METHODS.

In some of the systems previously described the complete speed range is in reality obtained by supplementing the principal method by a secondary one; as, for example, the multi-voltage systems which usually combine armature and field control. In such cases, however, it is evident which is the basic method and the systems have been classified accordingly.

In several industries specialized equipments have been developed to meet peculiar requirements of drive or automatic control. These systems do not involve new electrical combinations of the basic methods but are specialized in their mechanical applications and in the controlling equipments. The two-motor drives for printing presses, and the special steel-mill drives are examples. They will not be described here.

In the following system the two methods of armature and field control are so involved as to preclude classification under either of these heads.

Dunn Method of "Indirect Control".* This unique scheme proposed by Gano S. Dunn consists essentially in connecting the armatures of all the working motors in series, in a constant current circuit which is entirely independent of the fields. The fields are supplied from a separate constant potential circuit. In order that the speed may be constant under varying load, a small "regulating generator", B, is belted to the working motor, A, Fig. 27, and the generator armature is connected

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* U.S. Patents No. 549, 061, Oct. 29, 1895 and No. 591, 345, Oct. 5, 1897.

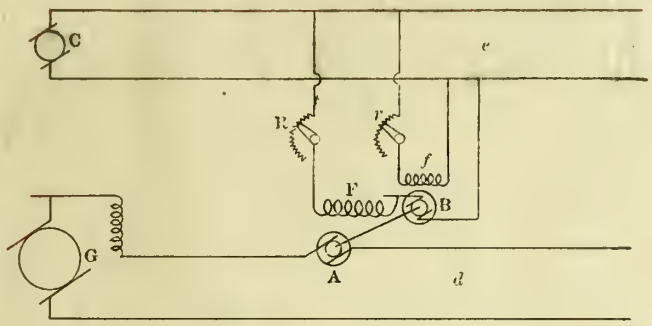

Fig. 27. Dunn Method of Indirect Control.

as a reversed "booster" in the field circuit of the working motor. The performance of such a system is very unusual. The armature voltage varies automatically with the load and the torque varies directly as the field strength at all times; hence the motor gives maximum speed and maximum torque with maximum strength of field.

Inherent Regulation: If the torque of the load be increased, the motor is called upon for increased torque, but it cannot automatically develop it because its torque is fixed by the constant armature current and the particular field strength for which its field rheostat is at the time adjusted. Since it cannot develop more torque by any change of speed, the motor must be stalled under such conditions unless the field strength be increased to such a point as to produce the new torque. This is accomplished automatically by the small auxiliary generator or regulating machine B. When the motor slows down, this generator slows down also; its e.m.f. is thus reduced and (since it is connected in opposition to the field circuit) the motor field is strengthened. The torque of the motor is thereby automatically adjusted to the required value to drive the load at the required speed. Should the speed exceed the value for which the apparatus is adjusted, the reverse operation is automatically performed, the torque of the motor being reduced by the weakened field, to just that value required by the load.

Adjustment of Speed: To increase the speed of the motor, the field is strengthened by cutting out a part of the resistance in rheostat, R, or to decrease the speed, the field is weakened by the same rheostat. For example, assume the motor to be operating a constant-torque load at a given speed, and that

we wish to double that speed. We will strengthen the motor field slightly and the motor will respond by speeding up, because it is developing more torque than the load requires and the additional torque is available for acceleration. The acceleration will continue until arrested by the regulating machine, B, at the speed for which the adjustments are made, as previously explained. Assuming that the speed has been doubled, the power output is also twofold. The armature current cannot change, but the voltage (counter e.m.f.) is doubled due to the increased speed. It is apparent that the field strength in such a case is varied only enough to provide the additional accelerating torque while the motor is speeding up, since the load-torque was assumed to remain unchanged.

The speed then is dependent upon the field strength only in so far as the different speeds involve different torque (due to windage, etc.) but any speed within certain limits may be obtained by so changing the torque as to produce an acceleration or permit a retardation to the desired speed, and then adjusting the torque to the torque of the load, which adjustment is automatically maintained by the regulating machine. The motor may be reversed by reversing its field.

This system should give any torque, at any speed, from zero to the limit of its output. It involves two distributing or supply systems, one of which must be supplied by a constant current generator, and if several motors are in series, a high voltage is necessary. The constant current system must, of course, carry the same current and have the same line losses, whether any motors are loaded or not.

TABLE VI.

Comparison of Torque-Speed Characteristics of General Methods of Varying Speeds.

(Assuming a constant I^2R loss in armature in each case at all speeds).

Method of Control		Condition	Speed	Torque	Horse power	
					Expressed as torque times speed	Expressed as % of maximum
E	Changing Volts "E" Impressed	E = 1	1	1	1	25
		E = 2	2	1	2	50
		E = 4	4	1	4	100
ø	Changing Flux "ø"	ø = 4	1	4	4	100
		ø = 2	2	2	4	100
		ø = 1	4	1	4	100
Y	Changing Conductors "Y" Series Parallel Windings Identical	Windings Series	1	1	1	50
		Windings Parallel	2	1	2	100
	Changing Conductors "Y" Series, then single. Windings in ratio 3:5. (Assumes windings same cross-section for simplicity).	Windings series	1	1.63	1.63	61.3
		Five turn winding alone	1.6	1.28	2.05	77.0
		Three turn winding alone	2.66	1.00	2.66	100.0

COMPARISON OF VARIABLE SPEED SYSTEMS.

Speed-Torque. In the interest of the best performance of a variable speed motor, its torque-speed characteristics should agree as nearly as possible with the characteristics of the load which it is to drive. The characteristics of variable speed motors, as influenced by different systems of control should therefore be carefully examined. These general relationships are summarized in Table VI for the three fundamental methods of speed variation, including two schemes of winding for that method which changes the number of armature conductors in series from brush to brush.

This summary shows the following facts:-

1. Speed control by changing the e.m.f. impressed on the armature gives constant torque at all speeds, and the power varies directly with the speed.

2. Speed control by changing field flux gives constant power at all speeds, and a torque varying inversely as speed.

3. Speed control by changing the conductors in series from brush to brush, (by means of two armature windings) gives characteristics which depend upon the particular arrangement used. The torque may be constant if the two armature windings are identical; or it may decrease somewhat as the speed increases, though at a rate less than inverse ratio, if the armature windings are unequal. The power varies directly with the speed in the first case, and in the same sense, though at a less rate, in the second case.

4. By no one of these methods alone is it possible to make the torque of a motor increase with an increase of speed.

5. Armature and field control are inherently different in their torque-speed characteristics and should not be compared on the same basis.

Inherent Regulation, which is another characteristic of importance, may be summed up in a general way, as follows:

Method "E" - Regulation variable - poor on low voltages,

Method "∅" - Regulation good at all speeds,

Method "Y" - Regulation good at all speeds.

Size of Motors. It has been broadly stated, by several writers, that a motor of standard design, to give constant output through a speed range of 2 to 1 by field control, must be four times as large as a fixed speed motor of the same output, whereas by armature voltage control, it need be only twice as large as would be required for the same output at the maximum speed. The deduction thus reached is that the size of motor required varies directly as the speed range by armature control, but as the square of the speed range by field control, so that the field controlled motor must be twice as large as the voltage controlled machine for a range of 2 to 1, and four times as large for a range of 4 to 1.

To illustrate, suppose 5 horse power is required throughout a range of 500 to 1000 r.p.m. By armature control a 10 h.p. at 1000 r.p.m. motor would have to be used, since the output would be reduced to half on half speed. By field control we would use a motor whose normal speed is 500 r.p.m., but in order to run sparklessly on half field strength, it is commonly assumed that the motor must operate at half load current; which means that it must be normally a 10 h.p. motor at 500 r.p.m.,

to be capable of delivering 5 h.p. with weakened field at a speed of 1000. But a 10 h.p. motor at 500 r.p.m. would be equal in size to a 20 h.p. motor at 1000 r.p.m. Hence a 20 h.p. size is said to be necessary by field control as compared with a 10 h.p. size by armature control.

These comparisons are based on the assumption that motors designed for constant speed duty are worked at their sparking limit as well as their heating limit on full field strength. But this assumption is not fully warranted. The average motor will stand a considerable increase of speed by field weakening without serious sparking. As an example, a standard 7 1/2 h.p. motor at 875 r.p.m. (or 3 1/2 h.p. at 400), which was rated by a certain manufacturer at 3 h.p. for variable speed machine tool service from 400 to 1600 r.p.m. was found to operate satisfactorily throughout the range. A motor of almost the same size would have been necessary with armature control.

It is, of course, understood that with special provision, such as commutating poles, for taking care of sparking, the same size of frame would be used for field control as for armature control to give constant horse power through any reasonable speed range.

In a paper before the Cincinnati Chapter of the American Institute of Electrical Engineers, Feb. 9th, 1903, Mr. William Cooper presented a graphical method of determining the minimum size of motor for any predetermined speed-range, by combining multiple voltage and field control in such proportions as to work the motor at its heating limit at the lower, and at its sparking limit at the upper end of the speed range. Mr. Cooper's curves are based on the assumption discussed above, viz., that

the size of the field controlled motor will be proportional to the square of the speed range.

For the requirement of constant torque throughout the speed range (power varying directly as speed), this matter of comparative sizes has a different aspect. For example, assume the requirement of constant torque through a range of 300 to 1200 r.p.m., the power being 5 h.p. at 300 and 20 h.p. at 1200. By armature voltage control, the motor would be a standard 20 h.p. at 1200 r.p.m. machine. By field control it would have to be a 20 h.p. at 300 r.p.m. motor having 4 times the armature current rating of the other motor in order to produce the required torque, with one-fourth normal field. The field controlled motor would be four times as large as the armature controlled, (20 h.p. at 300 r.p.m. requires the same size motor as 80 h.p. at 1200). This is on the assumption of an inter-pole or other special type of design for taking care of commutation. It is therefore plain that field controlled motors are not suitable for constant-torque loads.

Motors for Machine Tools. For machine-tool work the requirements are about as follows:-

Simple and convenient control,

Good speed regulation,

Wide speed range, say 4 to 1,

Sparkless commutation under overloads,

High efficiency at all loads and all speeds,

Compactness,

Simple distributing system,

Simple accessories,

Moderate first cost.

The majority of machine-tools have constant power characteristics, yet many require constant torque. It is hardly to be expected that any one system would fully meet all possible conditions. The four-wire multiple-voltage system falls short in several particulars. In speed regulation, simple control, efficiency, and simple distributing systems and accessories, it fails to fully measure up to the desired specifications. It is generally recognized, however, that for work where constant torque is required over a wide range of speed, multiple voltage has important advantages. Where constant power is the requirement, a system of field-flux control is decidedly superior to multiple voltage. A multi-voltage distributing system may have flux controlled motors connected to its outside wires and will thus provide both methods of control. Single-voltage distribution, while the simplest and least costly system, will serve double-commutator motors as well as those controlled by field weakening and will therefore fairly meet all conditions. Should the conditions indicate a compromise system of universal application, yet less costly than multiple-voltage, the result will be very well realized by equal voltage, three-wire distribution.

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